The Quantum Equivalence Principle

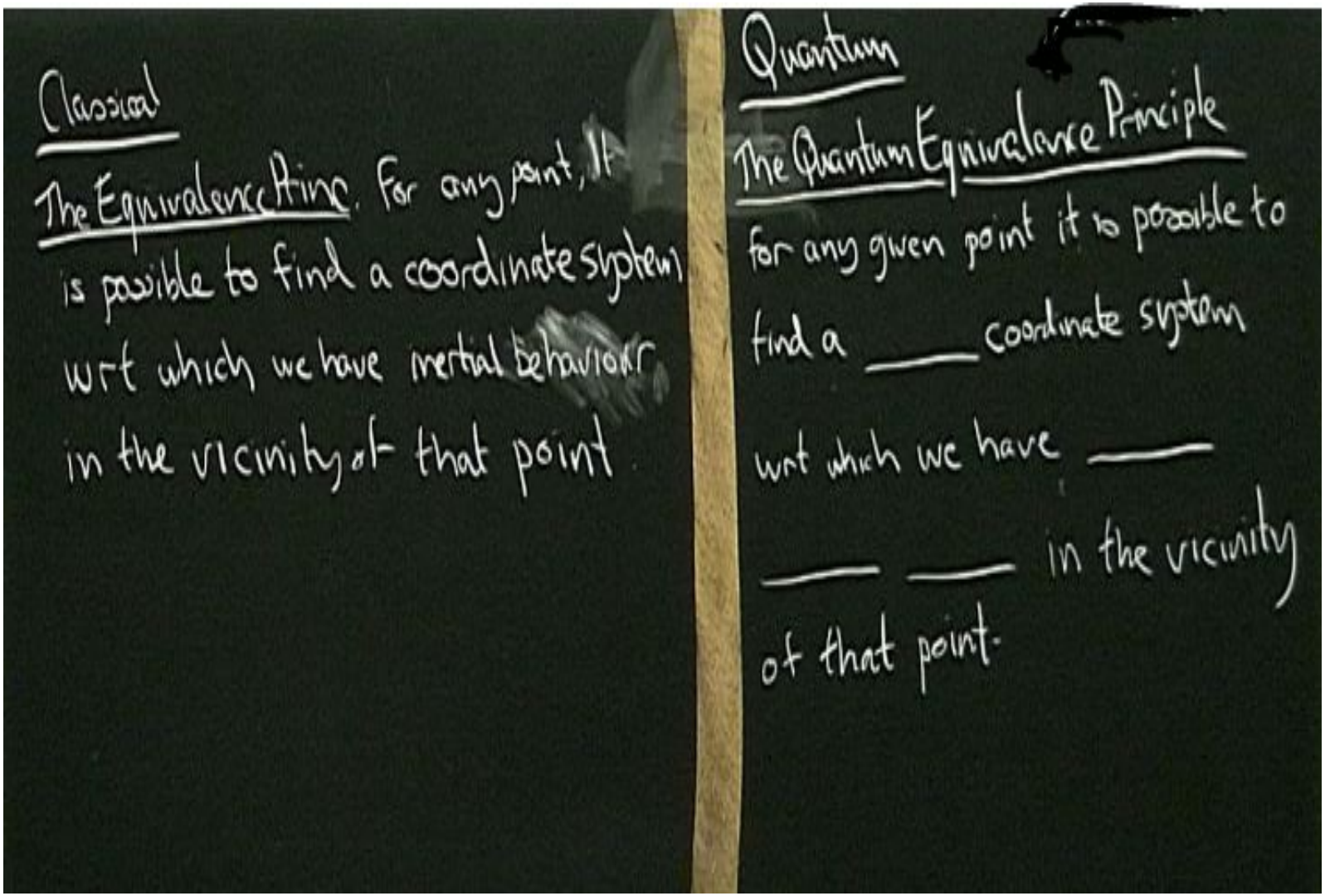
Lucien Hardy

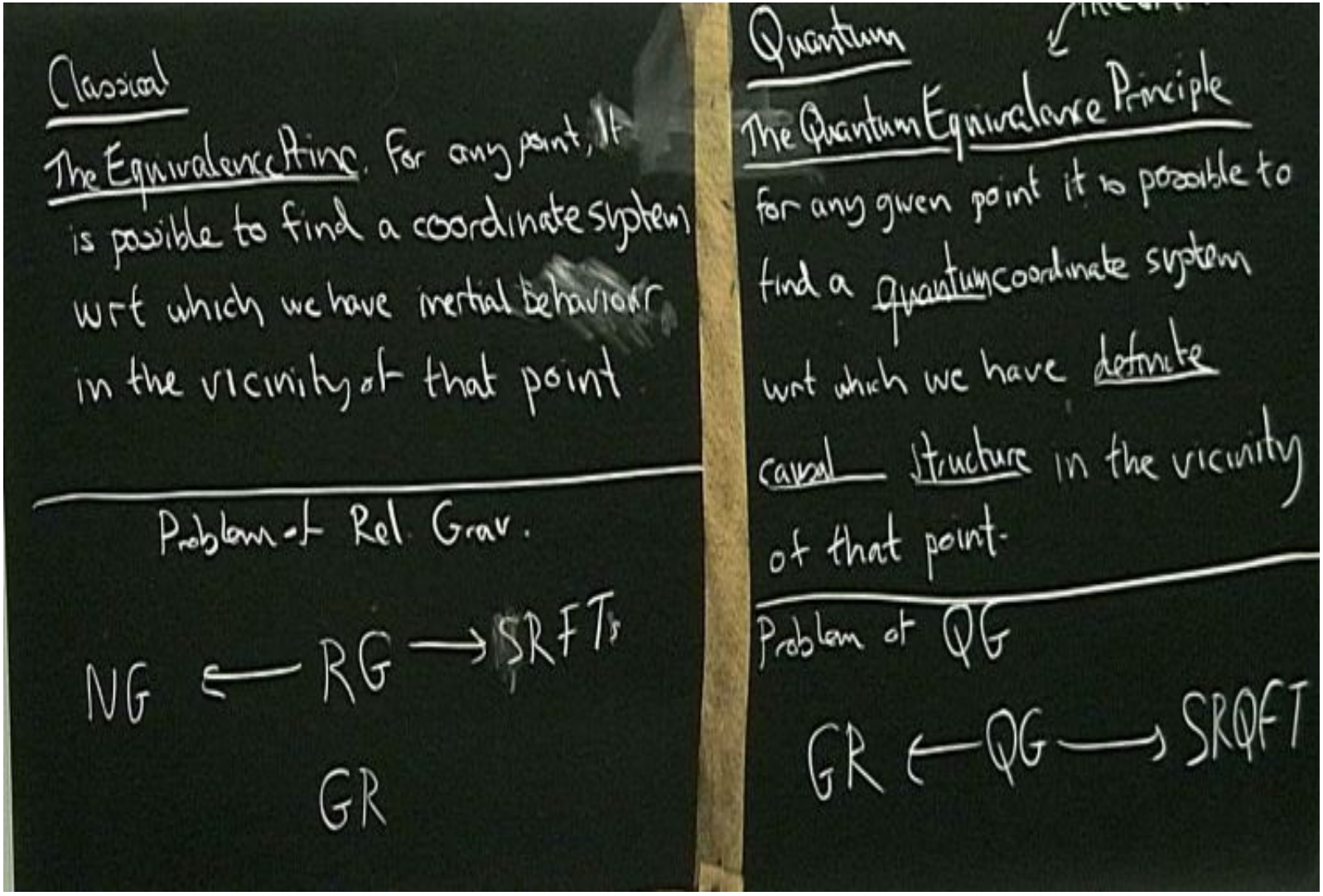
Perimeter Institute, Waterloo, Ontario, Canada

Taming the wild beast of indefinite causal structure

Lucien Hardy

Perimeter Institute, Waterloo, Ontario, Canada


Classical
The Equivalence Principle. For any point, it is possible to find a coordinate system wrt which we have inertial behaviour in the vicinity of that point.
Quantum
The Quantum Equivalence Principle
for any given point it is possible to find a ____ coordinate system wrt which we have ____ ____ ____ in the vicinity of that point.


Classical
The Equivalence Principle. For any point, it is possible to find a coordinate system wrt which we have inertial behaviour in the vicinity of that point.
Problem of Rel. Grav.
NG ← RG → SRFTs
GR
Quantum
The Quantum Equivalence Principle
for any given point it is possible to find a quantum coordinate system wrt which we have definite causal structure in the vicinity of that point.
Problem of QG
GR ← QG → SRQFT

The Problem of Relativistic Gravity

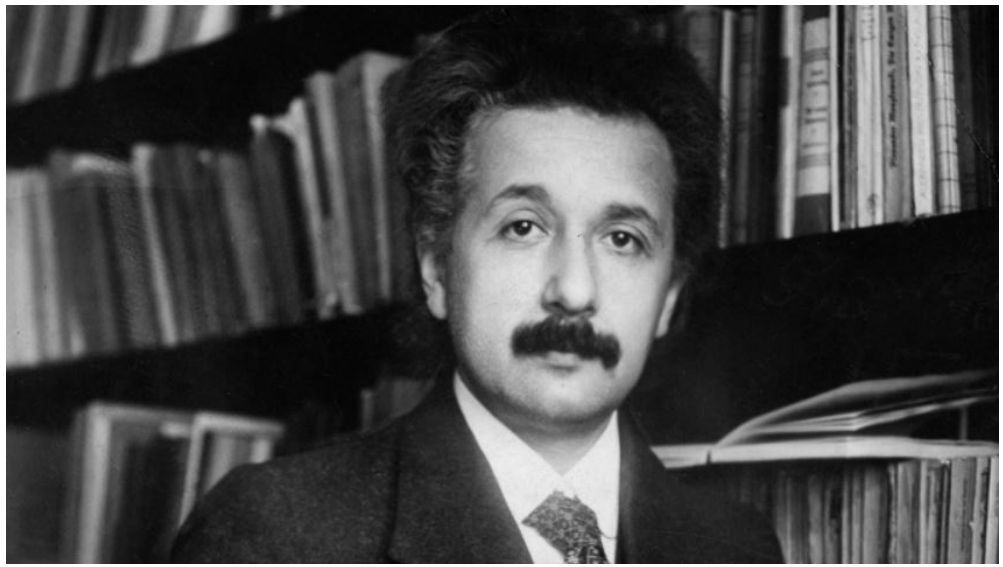
The problem faced by Einstein in early 1900's was this.

$$\text{Newton Gravity} \longleftarrow \text{Relativistic Gravity} \longrightarrow \text{Spec. Rel. Field. Th.}$$

Einstein's solution to this problem was the theory of General Relativity. The Equivalence Principle played a crucial role in this.

General Relativity

Albert Einstein 1915 (age 36).

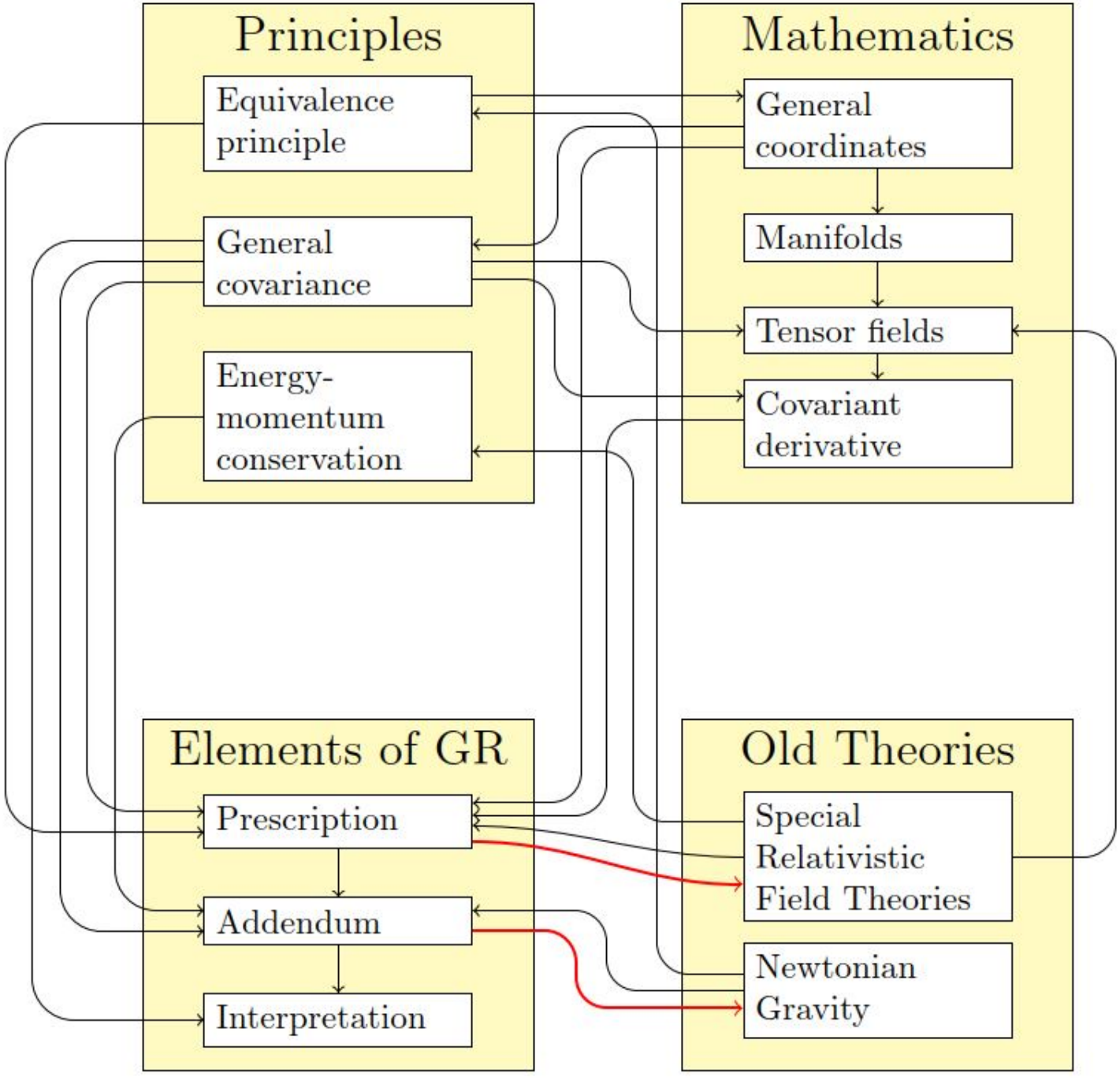


He completed possibly the most remarkable intellectual feat in history.
How did he do it?

Equivalence Principle - Einstein: "The happiest thought of my life"

The Equivalence Principle: *There always exists a coordinate system with respect to which we have inertial physics in the local vicinity of any given point.*

This reference frame is associated with a certain natural behaviour - that of falling bodies.


Principles
Equivalence principle
General covariance
Energy-momentum conservation
Mathematics
General coordinates
Manifolds
Tensor fields
Covariant derivative
Elements of GR
Prescription
Addendum
Interpretation
Old Theories
Special Relativistic Field Theories
Newtonian Gravity

Three Elements of General Relativity

General Relativity consists of three parts

A prescription to convert SR matter field eqns to GR matter field eqns.

$$\eta_{\bar{\mu}\bar{\nu}} \to g_{\mu\nu}$$

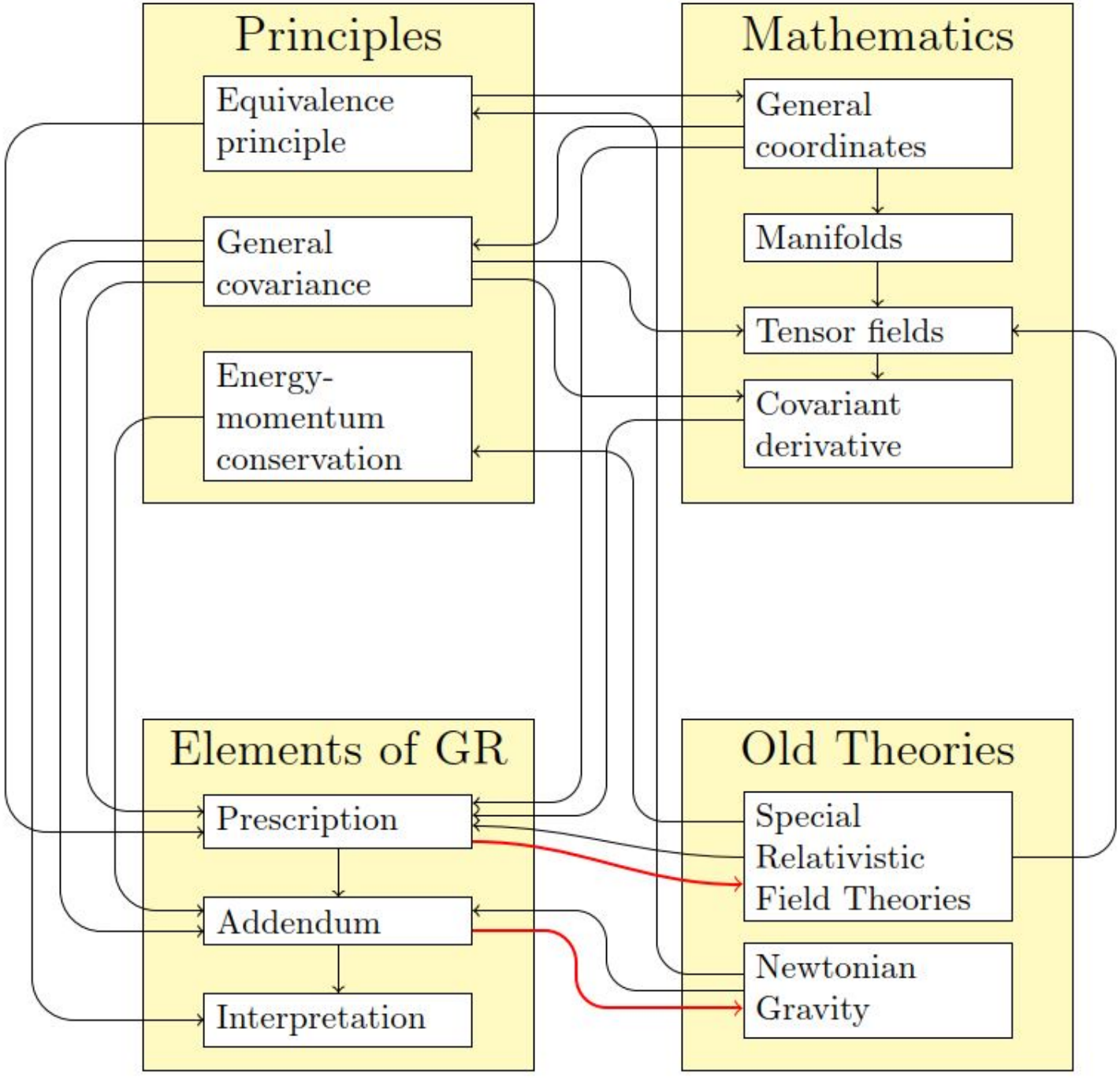
$$\partial_{\bar{\mu}} \to \nabla_{\mu}$$

$$x^{\bar{\mu}} \to x^{\mu}$$

An addendum. Now have an extra 10 real variables in $g_{\mu\nu}$ so need 10 equations

$$G^{\mu\nu} = 8\pi T^{\mu\nu}$$

An interpretation. Beables are those quantities that are invariant under general coordinate transformations.


Principles
Equivalence principle
General covariance
Energy-momentum conservation
Mathematics
General coordinates
Manifolds
Tensor fields
Covariant derivative
Elements of GR
Prescription
Addendum
Interpretation
Old Theories
Special Relativistic Field Theories
Newtonian Gravity

How does GR solve the problem of RG?

Newton Gravity $\longleftarrow$ Relativistic Gravity $\longrightarrow$ Spec. Rel. Field. Th.

- In limit of no gravity there exists a global inertial reference frame such that $\nabla_\mu = \partial_\mu$ and $g_{\mu\nu} = \eta_{\mu\nu}$ and recover Special Rel. Field Theory (this comes from the prescription).
- The Einstein field equations (in the addendum) limit to Poisson's equation for the Newtonian Gravitational potential as $c \to \infty$.

How does GR solve the problem of RG?

Newton Gravity $\longleftarrow$ Relativistic Gravity $\longrightarrow$ Spec. Rel. Field. Th.

- In limit of no gravity there exists a global inertial reference frame such that $\nabla_\mu = \partial_\mu$ and $g_{\mu\nu} = \eta_{\mu\nu}$ and recover Special Rel. Field Theory (this comes from the prescription).
- The Einstein field equations (in the addendum) limit to Poisson's equation for the Newtonian Gravitational potential as $c \to \infty$.

GR is even handed - it modifies both the less fundamental theories.

The Great Project Today is Quantum Gravity

The problem of Quantum Gravity

The problem of Quantum Gravity is to find a theory that limits to General Relativity and to Quantum Field Theory in appropriate limits.

General Relativity $\longleftarrow$ Quantum Gravity $\longrightarrow$ Spec. Rel. Quantum Field Th.

The problem of Quantum Gravity

The problem of Quantum Gravity is to find a theory that limits to General Relativity and to Quantum Field Theory in appropriate limits.

General Relativity $\longleftarrow$ Quantum Gravity $\longrightarrow$ Spec. Rel. Quantum Field Th.

This problem has much in common with the problem of Relativistic Gravity. Can we learn from Einstein?

My efforts

Since 2005, I have been pursuing an approach to Quantum Gravity motivated by the reconstruction project.

My efforts

Since 2005, I have been pursuing an approach to Quantum Gravity motivated by the reconstruction project.

- In 2005-8 I introduced the term *indefinite causal structure* to describe what I think is the main conceptual issue that has to be dealt with in Quantum Gravity. And I set up the causaloid framework for operational theories with indefinite causal structure. This is a GPT style framework.

My efforts

Since 2005, I have been pursuing an approach to Quantum Gravity motivated by the reconstruction project.

- In 2005-8 I introduced the term *indefinite causal structure* to describe what I think is the main conceptual issue that has to be dealt with in Quantum Gravity. And I set up the causaloid framework for operational theories with indefinite causal structure. This is a GPT style framework.
- In 2016 I showed how to provide an operational formulation of General Relativity for both the possibilistic and the probabilistic cases.

My efforts

Since 2005, I have been pursuing an approach to Quantum Gravity motivated by the reconstruction project.

- In 2005-8 I introduced the term *indefinite causal structure* to describe what I think is the main conceptual issue that has to be dealt with in Quantum Gravity. And I set up the causaloid framework for operational theories with indefinite causal structure. This is a GPT style framework.
- In 2016 I showed how to provide an operational formulation of General Relativity for both the possibilistic and the probabilistic cases.
- In 2018-9 I proposed the *Quantum Equivalence Principle* and provided one possible way to implement it. I also propose that we pursue a route to QG analogous to Einstein's route to GR.

My efforts

Since 2005, I have been pursuing an approach to Quantum Gravity motivated by the reconstruction project.

- In 2005-8 I introduced the term *indefinite causal structure* to describe what I think is the main conceptual issue that has to be dealt with in Quantum Gravity. And I set up the causaloid framework for operational theories with indefinite causal structure. This is a GPT style framework.
- In 2016 I showed how to provide an operational formulation of General Relativity for both the possibilistic and the probabilistic cases.
- In 2018-9 I proposed the *Quantum Equivalence Principle* and provided one possible way to implement it. I also propose that we pursue a route to QG analogous to Einstein's route to GR.

In recent years there has been a tremendous amount of progress on indefinite causal structure in Quantum Foundations community (boosted by papers by Chiribella, D'Ariano, Perinotti, Valiron, and by Oreshkov, Costa, and Brukner).

Conservative and radical features of GR and QT

	GR	QT
conservative	deterministic	fixed causal structure
radical	dynamical causal structure	probabilistic

.

Conservative and radical features of GR and QT

	GR	QT
conservative	deterministic	fixed causal structure
radical	dynamical causal structure	probabilistic

Expect QG to be a probabilistic theory with dynamical causal structure.

Conservative and radical features of GR and QT

	GR	QT
conservative	deterministic	fixed causal structure
radical	dynamical causal structure	probabilistic

Expect QG to be a probabilistic theory with indefinite causal structure.

Quantum Reference Frames

Study of Quantum Reference Frames goes back to Aharonov, Susskind, Kaufherr

Recent work by Giacomini, Castro-Ruiz, and Brukner is ground breaking. Flaminia Giacomini will speak about Quantum Reference Frames at 16:40.

We can transform from one quantum reference frame to another. What appears to be in a superposition in one quantum reference frame may be classical in another.

In the current theory these quantum reference frames apply at a given time.

Quantum coordinate systems

Einstein used (general) coordinate systems in setting up General Relativity. These cover space and time.

I want an analogous notion of (general) quantum coordinate systems.

In arxiv:1903.01289 I show one way to implement such quantum coordinate systems.

Classical description in General Relativity

The classical description of a spacetime is given by

$$u = \{(\Phi, p) : \forall p \in \mathcal{M}\}$$

where

$$\Phi = (\text{matter fields}, \text{metric field})$$

If we perform a diffeomorphism, $p \to \varphi(p) = q$ then this induces

$$\varphi^* u = \{(\varphi^* \Phi, q) : \forall q \in \varphi(\mathcal{M})\}$$

This is the same physical situation. If we have a coordinate system, this induces

$$x^\mu \to x^{\mu'}$$

Relabeling of points.

Classical description in General Relativity

The classical description of a spacetime is given by

$$u = \{(\Phi, p) : \forall p \in \mathcal{M}_u\}$$

where

$$\Phi = (\text{matter fields}, \text{metric field})$$

If we perform a diffeomorphism, $p \to \varphi(p) = q$ then this induces

$$\varphi^* u = \{(\varphi^* \Phi, q) : \forall q \in \varphi(\mathcal{M}_u)\}$$

This is the same physical situation. If we have a coordinate system, this induces

$$x^\mu \to x^{\mu'}$$

Relabeling of points.

Quantum Description

The path integral is

$$\int_{u \in V[a]} \mathcal{D}_u e^{iS/h}$$

where u is the classical description. The information in this path integral is included in the following object

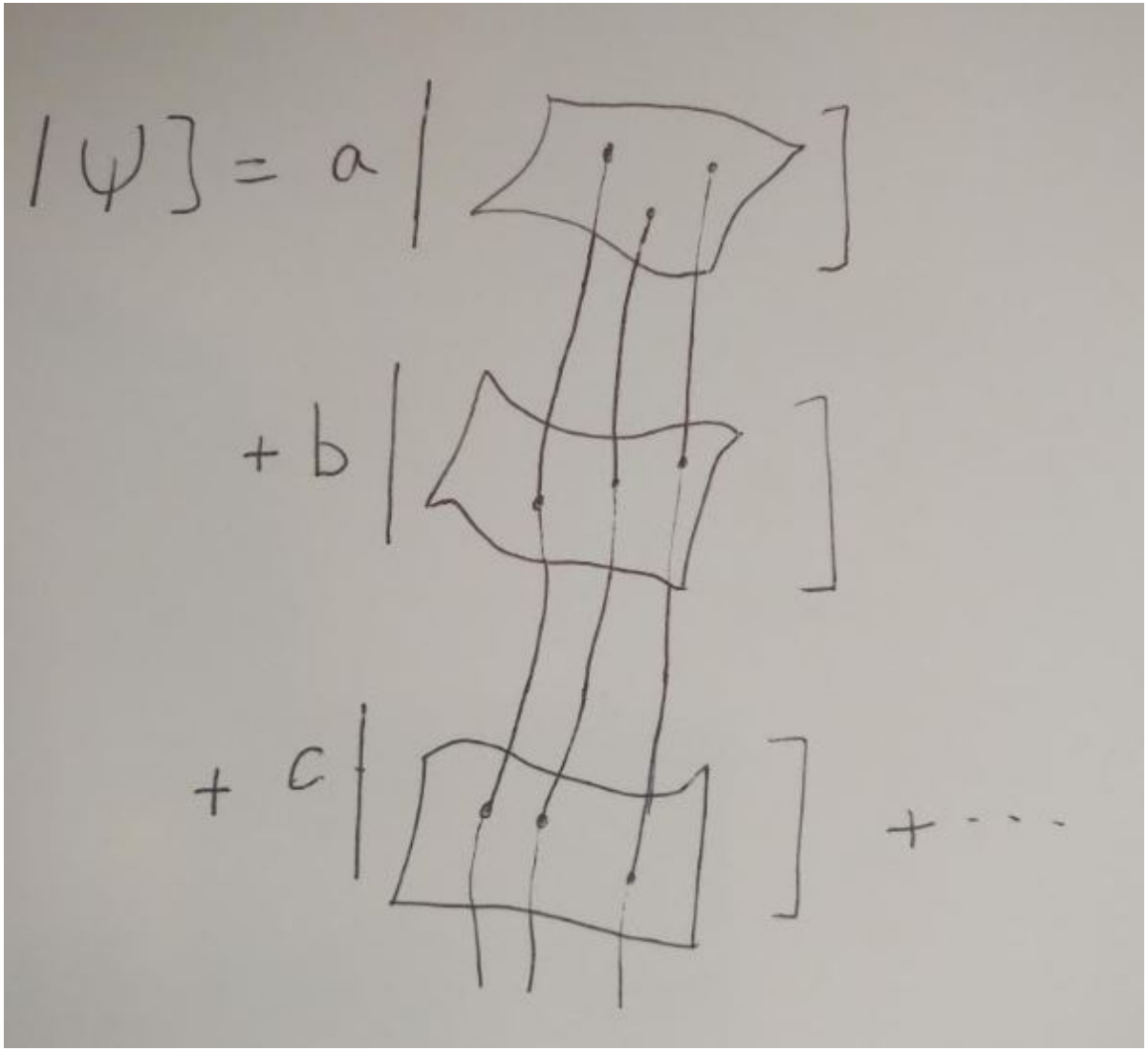
$$|\Psi] = \int \mathcal{D}u \; c_u \, |u]$$

We think of

$$|u]$$

as being a bit like a ket, $|n\rangle$ (except that $|u]$ is extended in space time).

Quantum coordinate systems



Quantum coordinate systems continued

A quantum coordinate system consists of two things.

1. An identification map between the points of the manifolds, $\mathcal{M}_u$, for the different $|u]$ (as in diagram).
2. A classical coordinate system.

Quantum coordinate system transformation

A quantum coordinate system transformation consists of

1. A re-identification of points between the $\mathcal{M}_u$
2. A transformation of the classical coordinate system.

Unlike in the classical case, points lose their identity under a quantum coordinate transformation.

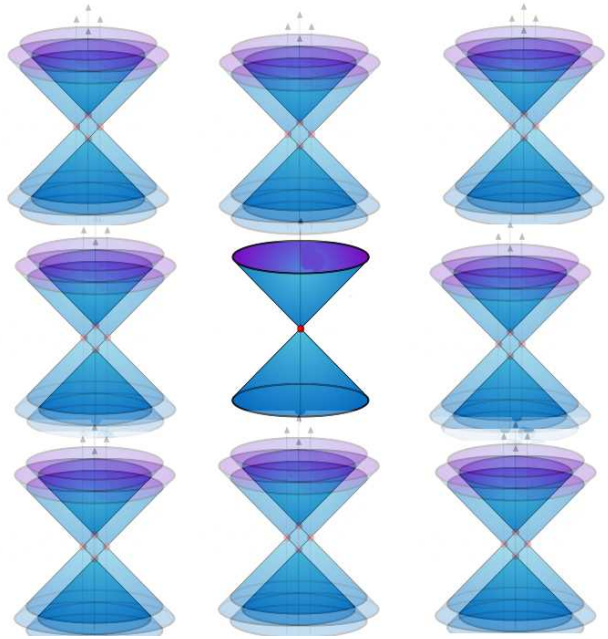
The Quantum Equivalence Principle

I propose the following

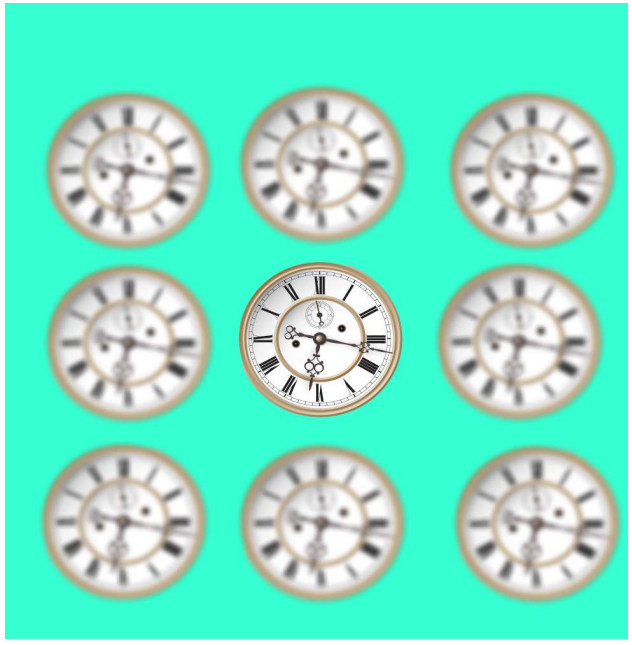
> **The Quantum Equivalence Principle**: *There always exists a quantum coordinate system with respect to which we have definite causal structure in the local vicinity of any given point.*

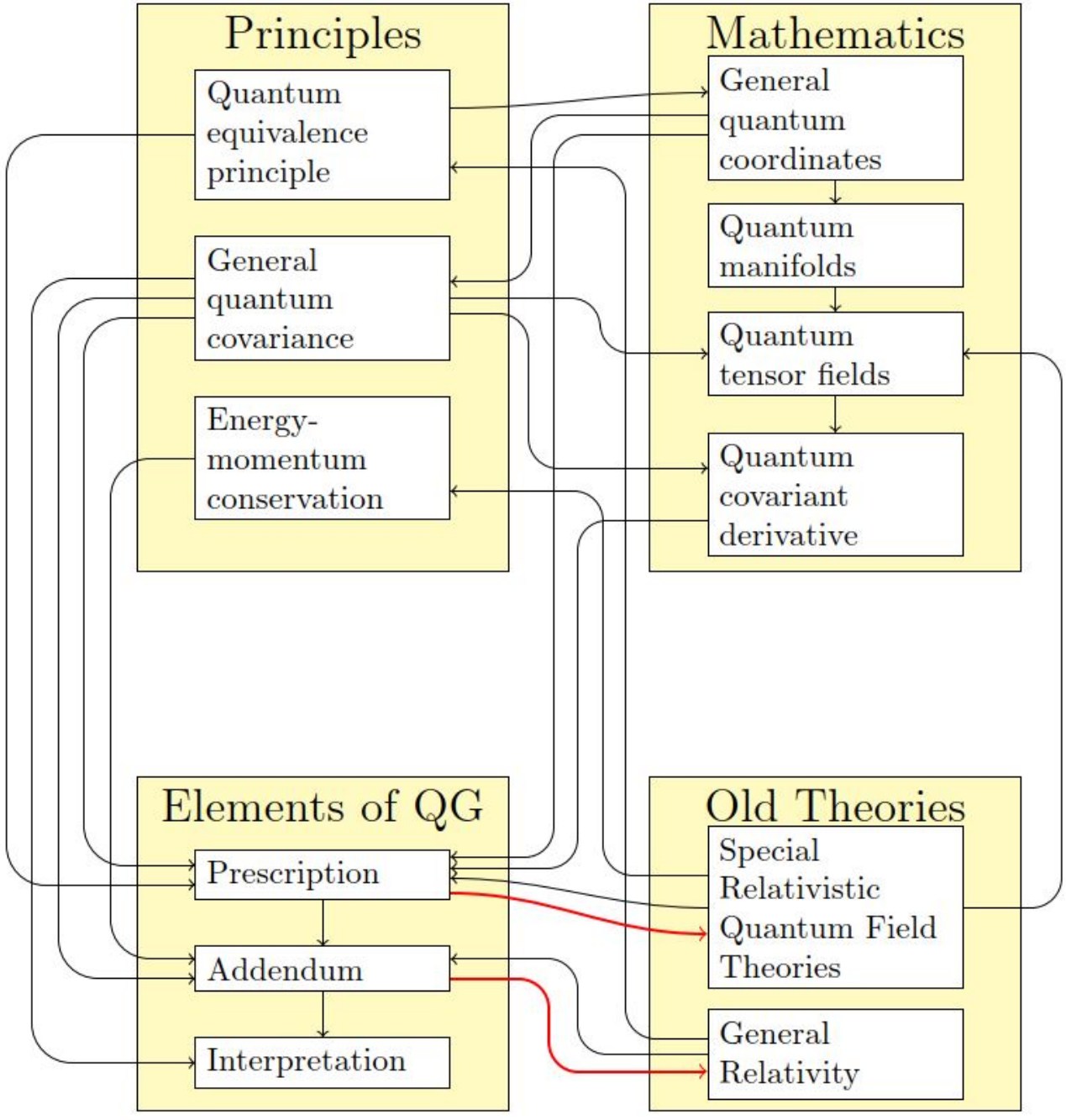
Implementing the quantum equivalence principle

Can locally get all the light cones to line up (at a given quantum coordinate) by applying an appropriate quantum coordinate transformation (that keep that point fixed and "rotate" the lightcones till they match).



If conformal factors also match up then clock at p has a definite rate.




Principles
Quantum equivalence principle
General quantum covariance
Energy-momentum conservation
Mathematics
General quantum coordinates
Quantum manifolds
Quantum tensor fields
Quantum covariant derivative
Elements of QG
Prescription
Addendum
Interpretation
Old Theories
Special Relativistic Quantum Field Theories
General Relativity

Three elements for Quantum Gravity?

A prescription to convert SR quantum matter field correspondence functions to GR quantum matter field correspondence functions.

replace $\eta_{\bar{\mu}\bar{\nu}} \to g_{\mu\nu}$ with quantum version

replace $\partial_{\bar{\mu}} \to \nabla_{\mu}$ with quantum version

replace $x^{\bar{\mu}} \to x^{\mu}$ with quantum version

An addendum. Now have some kind of quantum metric which introduces extra variables so need extra correspondence functions.

replace $G^{\mu\nu} = 8\pi T^{\mu\nu}$ with quantum version

An interpretation. Beables are those quantities that are invariant under general quantum coordinate transformations.

Speculation on the addendum

My speculation is that this addendum will provide causality conditions that generalize the causality conditions for fixed causal structure.

In particular, using the Quantum Equivalence Principle, it is possible to write down these causality conditions locally at a point in a quantum frame of reference that makes the causal structure definite in the vicinity of that point.

Speculation on the interpretation

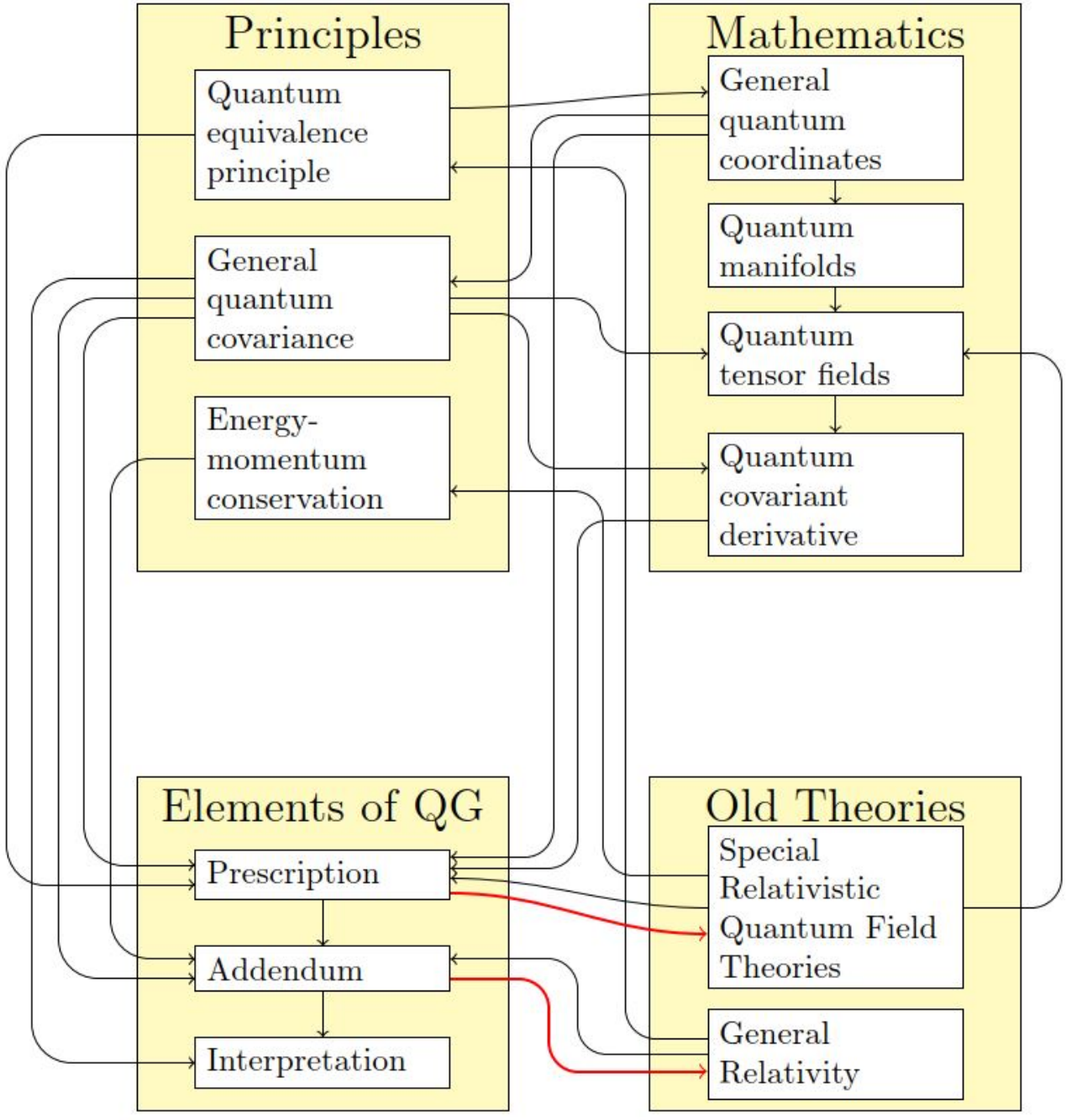
Beables are those quantities that are invariant under general quantum coordinate transformations.

The world, so constructed, may solve many of the interpretational problems of Quantum Theory.

My hope is that it will (i) solve the measurement problem (ii) provide a natural interpretation of quantum nonlocality.

Conclusions

It is a long road to Quantum Gravity.
But, with Einstein's help, maybe we will get there in the end.


Principles
Quantum equivalence principle
General quantum covariance
Energy-momentum conservation
Mathematics
General quantum coordinates
Quantum manifolds
Quantum tensor fields
Quantum covariant derivative
Elements of QG
Prescription
Addendum
Interpretation
Old Theories
Special Relativistic Quantum Field Theories
General Relativity